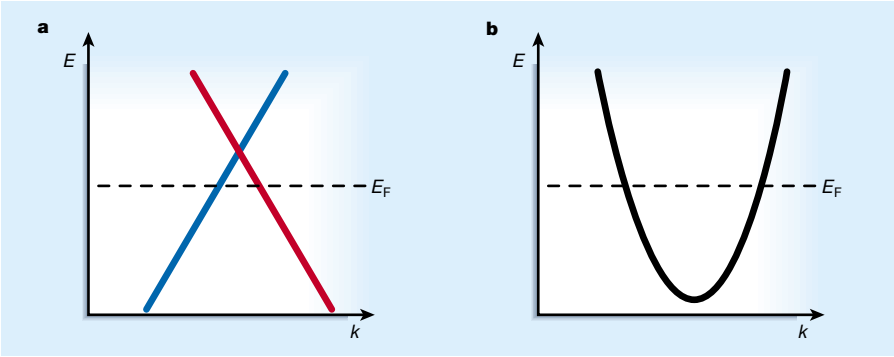

Figure 1 **Electron band structures of nanotubes and bulk metals.** a, **In a metallic carbon nanotube, left-moving electrons (red) and right-moving electrons (blue) belong to two different bands with distinct microscopic structures. Within each band, energy, *E*, is a linear function of momentum, *k*. Electrons are filled up to the Fermi level, E_F; this level is near the crossing of the bands, but may vary slightly depending on the environment of the tube. Another band crossing, at very different momentum, is (safely) ignored in our discussion.** b, **In a normal bulk metal, all electrons that contribute to conduction, both left-moving and right-moving, belong to a single parabolic band. In the new work, Lemay *et al.*[3] confirm theoretical predictions about nanotube band structure.**

allows individual electron wavefunctions to be imaged[7]. A wavefunction, $\psi(x)$, describes the position at which an electron with a given energy, E_ψ, is most likely to be found; the wavefunction squared is the 'probability density'. Areas of high probability density are those in which electrons easily tunnel into or out of the sample. To measure the probability density, the STM tip is again scanned over the sample. This time, as the tip scans the sample, the tip–sample voltage, V, is shifted slightly up and down — intentionally and periodically. The current, I, shifts in step with the voltage, and the ratio of the change in current to that in voltage (dI/dV) can be measured. An especially large oscillation in current indicates that electrons are tunnelling into or out of a quantum state in the sample.

Lemay and colleagues[3] performed this dI/dV analysis at three different settings of average tip–sample voltage, each probing a different electron energy in the nanotube. At each energy they scanned across the length and width of the tube, acquiring a distinctive image of spots and lines. The images matched the predicted form[8] of wavefunctions in nanotubes, showing frequent spatial oscillations with the expected period and orientation (see Fig. 1 of the paper, page 618). These are the first complete experimental images of electron wavefunctions in a nanotube.

More importantly, through detailed analysis of many wavefunction images, Lemay and colleagues have confirmed theoretical predictions[4] about the 'band structure' of nanotubes. Band structure describes the allowed states of electrons in terms of their energy and momentum: a given band has a unique energy for each momentum. Carbon nanotubes come in two flavours: semiconducting and metallic, depending on how the graphite sheet is wrapped up. Lemay *et al.* studied metallic tubes, which have two bands that intersect at a single point (Fig. 1a).

Why is the band structure of a nanotube of interest? For one thing, it is unusual. In normal bulk metal, electrons occupy a single, parabola-shaped conduction band (Fig. 1b). In a metallic nanotube, however, two distinct, linear bands cross. At a given energy, one of the linear bands carries left-moving electrons, the other right-moving ones. In addition, one band is constructed from molecular bonding states, the other from antibonding states, so that the wavefunctions of left- and right-moving electrons look very different on an atomic scale. This has an effect on electron behaviour: to switch its direction of movement, an electron must also switch from a bonding to an antibonding state (or vice versa). This restriction suppresses changes in direction, so an electron in a metallic nanotube tends to move persistently in one direction[9,10]. This situation resembles that of neutrinos, which are elementary particles of (almost) zero mass. Each neutrino's spin depends on its direction of motion[11] — changing direction requires a change of spin orientation. In contrast, in a normal metal, left- and right-moving electrons are part of the same parabolic band, have the same microscopic character, and are easily interconverted.

The linear, two-band configuration of metallic nanotubes was predicted[4] soon after their discovery. Earlier this year, Liang *et al.*[12] provided the first experimental evidence of this configuration by measuring patterns of interference in electron transport through nanotubes. Lemay and colleagues[3] have now provided a more direct verification. By analysing their wavefunction images, they detected interference between electrons in the two different bands. As a result of this interference, the net probability density oscillates slowly along the length of the tube. The effect is much like playing the same note simultaneously on two strings of a violin. If

100 YEARS AGO

We have received several papers by Prof. Sommerfeld, dealing with the theory of the diffraction of Röntgen rays. One of these is published in the *Zeitschrift für Mathematik und Physik*, xlvi. I, 2, and abstracts are also given in the *Physikalische Zeitschrift*, ii. The special problem which forms the subject of Prof. Sommerfeld's work is the mathematical investigation of the results of the hypothesis put forward by Wiechert and Stokes, according to which Röntgen rays consist in an impulsive disturbance propagated through the ether. The author considers the problem of diffraction past a screen in the form of a half-plane and allied problems, and compares his results with those found by Haga and Wind and others. The single non-periodic impulse may be said to represent one extreme case of ray-propagation, while the purely periodic wave represents the other extreme. While actual Röntgen rays and light rays probably only approximate to these extreme cases, the agreement between Prof. Sommerfeld's conclusions and experimental results affords considerable evidence in favour of the above theory of Röntgen rays.
From *Nature* 8 August 1901.

50 YEARS AGO

It has generally been assumed that the only carboxylic acid present in the fruit of Bramley's Seedling apple is malic acid; but in 1949, when examining chromatograms run in *n*-butanol-formic-acid-water (40 : 10 : 50 v/v) of methyl alcohol extracts of pulp tissue of young Bramley's Seedling apples, we noted that several spots having an acid reaction to bromophenol blue appeared on the chromatograms. In addition to a relatively large spot corresponding with malic acid (R_F = 0.49), there appeared a second well-defined spot (R_F = 0.18) and traces of a third spot (R_F = 0.07). It was possible to wash some of the acid (R_F = 0.18) from the chromatogram and carry out tests on the solution so obtained… It would appear, therefore, that the new acid might well be a dihydroxy tricarballylic acid. The acid appeared to decrease in amount as the fruit ripened and also appeared to be present in the pulp of the fruit of peach and plum. One of us has since examined other varieties of English apples for the presence of the new acid. It has been found in much greater quantity in young Worcester Pearmain and young Cox's Orange Pippin apples.
From *Nature* 11 August 1951.